

A Late-Time Flattening of Afterglow Light Curves

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ABSTRACT

We present a sample of radio afterglow light curves with measured decay slopes which show evidence for a flattening at late times compared to optical and X-ray decay indices. The simplest origin for this behavior is that the change in slope is due to a jet-like outflow making a transition to sub-relativistic expansion. This can explain the late-time radio light curves for many but not all of the bursts in the sample. We investigate several possible modifications to the standard fireball model which can flatten late-time light curves. Changes to the shock microphysics which govern particle acceleration, or energy injection to the shock (either radially or azimuthally) can reproduce the observed behavior. Distinguishing between these different possibilities will require simultaneous optical/radio monitoring of afterglows at late times.

Subject headings: gamma rays:bursts—radio continuum: general—ISM:jets and outflows—shock waves

1. Introduction

One of the defining characteristics of X-ray and optical afterglows is the observed power-law decay of their light curves. On timescales of hours to days after a burst the exponent α (defined by $F_\nu \propto t^\alpha$) typically lies in the range of -1 to -2 . The light curves of several GRBs have also been seen to undergo an achromatic break, steepening their temporal decay by $\Delta\alpha \sim 1$. The standard afterglow model provides a framework in which to interpret these power-law slopes and their changes. Synchrotron emission is produced in a relativistic shock which accelerates electrons to a power-law distribution with energy index p given by $N(\gamma_e) \propto \gamma_e^{-p}$ above some minimum energy γ_m . The evolution of the expanding blast wave

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is sensitive to the geometry of the shock, the kinetic energy in the shock, and the structure of the circumburst medium. This leads to the temporal (and spectral) evolution of the light curves whose power-law indices are predicted for different cases (Sari, Piran & Narayan 1998; Sari, Piran & Halpern 1999; Chevalier & Li 2000). The most commonly accepted explanation for the sharp breaks in optical and X-ray light curves is that the outflows are collimated and that the change in α is the result of the Lorentz factor Γ dropping below θ_j^{-1} , the inverse opening angle of the jet (Rhoads 1999). However, it should be noted that the jet signature is not identified unambiguously in all bursts, and for some events there are alternate explanations for the origin of the break (Kumar & Panaitescu 2000; Masetti *et al.* 2001; Wei & Lu 2002).

The situation at radio wavelengths is slightly more complex. Initially, at least, the emission comes from the lowest energy electrons at γ_m which are radiating only a small fraction of their energy at radio frequencies below ν_m . This gives rise to the familiar spectral slopes of $\nu^{1/3}$ and ν^2 in the optically thin and thick part of the radio spectrum, respectively, and it produces light curves that rise with time. A jet break is expected initially to produce only a shallow power-law decay (e.g. $t^{-1/3}$ to t^0) of the radio light curve until a time when the synchrotron peak ν_m passes through the band. If the expansion remains relativistic, the post-jet power-law decay α_R will be the same as that at optical and X-ray wavelengths (*i.e.*, $\alpha \sim -2$)

In addition to the late onset of the steep jet decay, it may be possible to use the long-lived nature of the radio emission to look for changes in α when the expanding shock slows to subrelativistic speeds (Waxman, Kulkarni & Frail 1998). Deviations in the power-law decay could also be produced by density enhancements in the circumburst medium on parsec scales, similar to that seen in supernovae (Montes *et al.* 2000). Likewise, it is possible that the bulk of the GRB blast energy is in a low Γ component and that the late-time afterglow will be refreshed as this slower shock catches up to the decelerating swept-up shell. There may also exist an additional low energy electron component (Waxman 1997; Bhattacharya 2001; Li & Chevalier 2001; Panaitescu 2001), which while energetically unimportant it could significantly modify the late-time afterglow light curves. Finally, all of these processes could be masked by the emergence of an underlying host galaxy, whose radio emission is the result of prodigious star formation.

Motivated by the possibility of detecting these effects at late times, we have analyzed a set of well-sampled GRB radio light curves for which it is possible to measure their temporal decay indices. In §2 we compare the sample of X-ray and optical afterglows, while in §3 the comparison is carried out with the radio and optical afterglow sample. In §4 we discuss known sources of biases that affect decay slope measurements, while in §5 and §6 we discuss

possible explanations for the observed flattening of the radio light curves.

2. An X-ray/Optical Comparison

In Table 1 we provide a list (complete until 2002 January) of all afterglows with accurately measured temporal decay indices at both X-ray and optical wavelengths. Most of the X-ray measurements were obtained between 8 and 24 hours after the burst. For the optical data we list the time interval over which the power-law fit was made. If a jet break occurred in the light curve, two values of α_o are given along with the relevant timescale. When required, a constant emission component from a host galaxy was also fit to the optical light curves.

In the top panel of Figure 1 we show a plot of α_x versus α_o . Most of the points are distributed about the line $\alpha_x = \alpha_o$ with small scatter but there are a few significant deviations where the X-ray decay is steeper than the optical decay. For reasonable physical parameters for the shock in a constant density medium, the synchrotron cooling frequency ν_c is expected to lie between the optical and X-ray bands on these timescales (Panaiteescu & Kumar 2001). The temporal slope of light curves measured above ν_c will be steeper by an amount $\Delta\alpha=1/4$ (Sari et al. 1998), consistent with all points which lie above the fiducial $\alpha_x = \alpha_o$ line.

More than half of the points in Fig. 1 have a tendency to lie below the $\alpha_x = \alpha_o$ line. In the simplest afterglow models α_o is not expected to be steeper than α_x . We could expect such a result if the shock wave were propagating into a density gradient, such as that produced by mass loss from a progenitor star. For reasonable physical parameters ν_c is expected to lie below the optical band for the timescales of interest here (Li & Chevalier 2001). A more plausible explanation is that inverse Compton emission, which has been reported for several bursts (e.g., Harrison et al. 2001), is producing a slight flattening the X-ray light curves. Finally, for GRB 980519 it is likely that the jet break occurred close to the time of the X-ray measurements (Nicastro *et al.* 1999; Jaunsen *et al.* 2001) producing an estimate of α_x that is intermediate between the two asymptotic values.

3. A Radio/Optical Comparison

The 10 afterglows in Table 1 were selected from Frail et al. (2003) to have well-sampled light curves at a frequency of 8.5 GHz. The remaining 15 GRBs in this catalog do not have sufficient measurements to determine a decay index α_R at late times. A least-squares fit was made to each dataset. In order to be as free as possible from interstellar scintillation and

deviations from power-law decay due to curvature effects in the synchrotron spectrum (see §4), each burst was fit to several different starting epochs. The final values of α_R listed in Table 1 were often a compromise between making the starting epoch as late as possible while including sufficient data points for a fit. In Figure 2 we show the results of our fits for the four best sampled events. The reduced χ^2 ranges from 0.6 to 1.3, typical of the sample as a whole.

In the bottom panel of Figure 1 we show a plot of α_R versus α_o . The optical decay index was chosen over α_x for this comparison because there are more joint radio/optical datasets and because their lightcurves are taken over similar timescales. Nonetheless, for the discussion that follows it is important to realize that the overlap between the optical and radio time intervals is relatively small. This will complicate attempts to understand the relation between α_o and α_R (see §6).

There is a clear trend in Figure 1, namely the radio decay indices are equal to or substantially flatter than the optical (or X-ray) decay indices. Moreover, the α_R values rarely exceed -1 and there are no examples of $\alpha_R \sim -2$. The data can be grouped into three different regions in Figure 1. The first are those with $\alpha_R \simeq \alpha_o$, the second have $\alpha_o < -2$, and the third group have $\alpha_o > -2$. In the next several sections we discuss several possible explanations for the origin of these temporal slopes.

4. Systematic Sources of Light Curve Flattening

Some of the measured α_o values are not as steep as is expected for a jet break due to the presence of a host galaxy, which for most events dominates the optical light curves typically between one week and one month after the burst. In those cases, contamination from the host galaxy may prevent a true determination of the post-jet α_o . Radio data have been used in several cases (e.g., GRB 000418 and GRB 980703) to further substantiate claims of jet breaks (Berger *et al.* 2001; Frail *et al.* 2003) but removing the host galaxy contribution is often difficult. A second source of flattening for optical light curves may be the excess of optical flux at $\sim 20(1+z)$ days, commonly attributed to the rise of a supernova component (e.g. Bloom *et al.* 2002).

A host galaxy may also flatten the late-time radio light curves. For GRB 980703 there is good evidence that the fit requires an additional contribution from an underlying galaxy (Berger, Kulkarni & Frail 2001). A starburst host galaxy has also been proposed for GRB 000418 (Berger *et al.* 2003). However, while the submillimeter detection of the host is robust, in our view further multi-frequency radio observations are required before the

centimeter identification of a host can be considered certain. Adding a host component to the GRB 000418 fit yields $\alpha_R = -1.72 \pm 0.09$ and $f_{host} = 37 \mu\text{Jy}$.

We do not expect radio galaxies to be detected as frequently as those at optical wavelengths. In order to significantly flatten the α_R values in Table 1 we require $F_{host} \sim 30 - 40 \mu\text{Jy}$, which at 8.5 GHz for the typical redshifts of these events, requires $\text{SRF} \sim 10^3 M_\odot \text{ yr}^{-1}$, or $L_{bol} > 10^{12} L_\odot$. If GRBs trace star formation in the universe, as is currently believed, then only about 20% of GRBs are expected to be found in such ultraluminous host galaxies (Barnard *et al.* 2003). This fraction is in good agreement with a more direct determination from centimeter and submillimeter observations of GRB host galaxies (Berger *et al.* 2003). Thus we expect that one, perhaps two, afterglows in our sample have undetected host galaxies. Fortunately, continued multi-frequency radio monitoring can be used to detect and subtract off any galaxy contribution.

A second, more insidious, problem is to ensure that α_R is not measured when the light curve is in transition between two power-law behaviors. For example, in the case a jet-like outflow there is a timescale t_j when the edge of the jet becomes visible and the optical emission steepens to $\alpha_o = -p$. In contrast at this time, the radio flux (which is typically emitted below the synchrotron peak ν_m at this time) decays with $\alpha_R = -1/3$ until ν_m passes through the radio band, after which it decays as $\alpha_R = -p$ in the relativistic phase or as $\alpha_R = (21 - 15p)/10$ in the sub-relativistic phase. Fits which encompass any of these transitions will give values of α_R which are in between these extremes.

An artificial flattening of the light curve will be measured if the fit is made before ν_m passes through the radio band. If ν_m passes through the optical band at a time t_o it is straightforward to show that for a jet ν_m passes through 8.5 GHz at $t_R \simeq 230 t_j^{1/4} \times t_o^{3/4}$ days provided $t_o < t_j < t_R$. Thus for typical shock parameters we expect $t_R \sim 5 - 30$ days (Sari *et al.* 1999). Most of the fits in Table 1 were made at a time $t > t_R$ but we caution the reader that the shallow α_R values for at least two GRBs may be the result of fitting over this transition. The only way to improve on these fits is to reduce the dependence on earlier measurements through deep observations of the faint afterglow emission at late times.

5. A Dynamical Origin for the Late Decay Slopes

A change in the temporal slope is expected in the basic afterglow model when the expansion of the blast wave becomes subrelativistic. This dynamical transition has been predicted for some time (Wijers, Rees & Mészáros 1997), and it has been claimed to have been seen in a number of events (Frail, Waxman & Kulkarni 2000; Dai & Lu 2000; Piro *et*

al. 2001, Int’Zand et al. 2001). This occurs on a timescale when the rest mass energy swept up by the expanding shock becomes comparable to the initial kinetic energy of the ejecta. For kinetic energies of 10^{51} and circumburst densities of 1 cm^{-3} this occurs on a timescale of order 100 days. After this time the dynamical evolution of the shock is described by the Sedov-Taylor solutions rather than the relativistic formulation of Blandford & McKee (1976).

Independent of geometry, the expected temporal slope in the non-relativistic regime is $\alpha_{NR} = (21 - 15p)/10$ for a constant density (ISM) medium, and $\alpha_{NR} = (5 - 7p)/6$ for a wind-blown medium (*i.e.*, $\rho \propto r^{-2}$). These values assume that the synchrotron break frequency ν_m has passed through the band but the cooling frequency ν_c remains above the band. Livio & Waxman (2000) provide a convenient table of α ’s for different cases.

For a spherical fireball undergoing a transition to non-relativistic expansion, the light curves are expected to *steepen* by $\Delta\alpha \simeq 0.3$, while for a jet-like expansion the light curves are expected to *flatten* by $\Delta\alpha \simeq 1$. By and large the α_R values in Table 1 are flatter than the α_o (and α_X) values measured at earlier times. This immediately rules out a spherical geometry for the majority of bursts in Table 1 with measured α_R values. For a jet-like outflow it is expected that $\alpha_o \simeq -p$ (for $t > t_{jet}$) and therefore the values of α_{NR} can be calculated and compared to α_R . For bursts with $\alpha_o \simeq -2.2$ (GRB 991208, GRB 00031C, GRB 000418 and GRB 000926) we expect $\alpha_{NR} \simeq -1.2$ in the ISM model and $\alpha_{NR} \simeq -1.7$ in the wind model. From Fig. 1 we note that at least for these GRBs the JET+ISM model provides a better (but not ideal) fit to the observed α_R values than a JET+WIND model. The deviations are in the sense that the observed α_R are systematically more shallow than expected from the α_o measurements. This is not likely to be a systematic bias because it is in the opposite sense of what would be expected if the optical decay was still in transition to its asymptotic value (*i.e.*, $\alpha_o > -p$). The JET+ISM model may also explain events like GRB 980703 for which there is good evidence that the temporal slope α_o is underestimated because the optical light curves are contaminated by an underlying host galaxy (§4).

A simple jet model does not work for GRB 970508, for which $\alpha_x > \alpha_o \simeq \alpha_R$. We note that both the optical and radio temporal slopes were measured at comparatively late times and therefore *both* of the fits may be dominated by points when the afterglow was in the sub-relativistic phase. In this case a near-spherical shock with $p \simeq 2.3$ provides a good description of the light curves (Frail et al. 2000, but see Chevalier & Li 2000). The most difficult challenge for the JET+ISM model comes from the third cluster of GRBs in Fig. 1 with $\alpha_o > -2$. In two cases (GRB 010222, and GRB 000911) adopting $\alpha_o \simeq p$ yields estimates of α_{NR} that are substantially flatter than the observed α_R values. The JET+WIND model works better but it is not clear that this model can explain the pre-jet behavior of the light

curves.

To summarize, while a sub-relativistic transition of a jet-like outflow in a constant density medium provides a reasonable explanation for the flattening of the radio light curves for some of the GRBs significant departures from this behavior are seen (e.g. GRB 000926). The radio slopes are substantially flatter than expected in this simple model and some other source must be found.

6. Alternate Origins and Conclusions

In the previous sections we have presented evidence that the temporal decay of radio light curves measured months after the burst show evidence for a flattening compared to the decay slopes measured at optical and X-ray wavelengths within the first week after the burst. The simplest explanation, consistent with most of the data, is that the flattening is the result of a dynamical transition of the shock to sub-relativistic expansion.

There are other physical effects that may lead to the flattening of radio lightcurves. Several authors (Bhattacharya 2001; Li & Chevalier 2000; Panaitescu 2001; Dado, Dar & De Rújula 2003) have modified the electron energy distribution by introducing a break in the power-law below which the spectrum is hard (*i.e.*, $p < 2$). This has the virtue of requiring no additional source of energy while simultaneously fitting for the different decays slopes in the X-ray, optical and radio bands. Its disadvantages are that it requires the introduction of another free parameter in the modeling, and that current simulations of particle acceleration in ultrarelativistic shocks are unable to produce hard energy spectra (Achterberg *et al.* 2001). Other modifications to the shock microphysics are possible (Rossi & Rees 2003). For example, Yost *et al.* (2003) have relaxed the usual assumption that the magnetic energy density behind the shock is constant, and note that the late-time light curves flatten when the magnetic energy grows inversely with the Lorentz factor of the shock.

The flattening could also be maintained by a continuous or episodic injection of energy, rather than the one-time injection as is commonly assumed (Rees & Mészáros 1998; Sari & Mészáros 2000; Kumar & Piran 2000). Slower moving shells of ejecta catch up to the decelerating main shock and re-energize it, causing to afterglow to brighten at all wavelengths (e.g. Panaitescu, Mészáros & Rees 1998). This “refreshed shock” model has been invoked to explain the optical behavior of GRB 010222 (Björnsson *et al.* 2002) and GRB 021004 (Fox *et al.* 2003). This explanation is problematic for the radio flattening because it requires continuous energy injection but with a delayed turn-on in order to both maintain the shallow decay of the radio light curve, while preserving the steeper optical decay. One way to

overcome this difficulty would be to add energy through a two component jet-like outflow, with the radio emission originating from an outflow with a wide opening angle carrying the bulk of the energy. This was first proposed for GRB 991216 (Frail *et al.* 2000), but Berger *et al.* (2003) recently have made a stronger case for GRB 030329. Since the bulk of the energy in this case is carried by the slower moving ejecta a crucial test would be to carry out a minimum energy analysis like for GRB 970508 (Frail *et al.* 2000) and look for large excesses compared to energies derived from conventional methods (Panaitescu & Kumar 2002; Frail *et al.* 2001).

In principle it should be possible to distinguish between these alternate explanations for the observed flattening. A dynamical transition is achromatic, and so a break in the optical and radio light curves should occur at the same time. A modified electron spectrum will produce two spectral components, recognized by comparing the spectral slopes both within and between the radio and optical bands. Energy injection, added either radially via refreshed shocks, or azimuthally from complex jet structure, will most likely be identified from multi-component light curves. All of these tests require near-simultaneous optical and radio light curves but as is evident from Table 1 such data is currently lacking. Although there are several practical problems to overcome (§4), future monitoring of optical afterglows should be extended to produce a better overlap with the late-time radio measurements. The recent bright and nearby GRB 030329 is a promising candidate.

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Table 1. X-ray, Optical and Radio Decay Slopes

GRB	α_X	α_o	Epoch (days)	α_R	Epoch (days)	Ref.
970228	-1.33 ± 0.12	-1.58 ± 0.28	1-5	...	...	1,2
970508	-1.1 ± 0.1^a	-1.30 ± 0.05	2-120	-1.34 ± 0.10	115-309	3,4
971214	-0.96 ± 0.15	-1.20 ± 0.02	0.5-3	...	...	5,6
980329	-1.35 ± 0.03	-1.21 ± 0.13	0.7-10	-1.15 ± 0.17	55-121	7,8
980519	-1.83 ± 0.3	-2.05 ± 0.04	0.35-2	...	...	9,10
980703	-1.24 ± 0.18	-1.61 ± 0.12	0.8-10	-1.33 ± 0.06^b	27-210	5,11
990123	-1.41 ± 0.05	-1.10 ± 0.03	0.18-2	...	...	5,12
990510	-1.0 ± 0.1	-0.82 ± 0.02	0.15-1.2	...	...	13,14
991208	...	-2.2 ± 0.1	2-7	-1.07 ± 0.09	53-293	15
991216	-1.61 ± 0.06	-1.22 ± 0.04	0.4-2	...	...	16,17
	...	-1.80 ± 0.30	2-15	-0.85 ± 0.16	8-78	
000301C	...	-2.29 ± 0.17	4-13	-0.93 ± 0.12	45-165	18
000418	...	-1.41 ± 0.08^c	2-14	-1.05 ± 0.10	75-202	19
000911	...	-1.46 ± 0.05	1-15	-0.91 ± 0.13	3-23	20
000926	-1.89 ± 0.18	-2.38 ± 0.07	2-30	-0.76 ± 0.08	25-288	21,22
010222	-1.33 ± 0.04	-1.57 ± 0.04	1-50	-0.55 ± 0.09	5-206	23,24

Note. — The columns are (left to right): (1) GRB name, (2) the X-ray temporal decay index defined by $F_X \propto t^{\alpha_X}$, (3) the optical temporal decay index, (4) the timerange over which the power-law fit was made to the optical light curves, (5) the radio temporal decay index, (6) the fit timerange, (7) references for the X-ray and optical decay slopes.

^a The X-ray decay index for GRB 970508 is approximate since there was substantial temporal and spectral variability for this burst. ^b Based on the findings of Berger, Frail & Kulkarni (2001), we subtracted a constant component for the host galaxy of this burst. ^c Berger *et al.* (2001) find evidence for a jet break at $t \sim 26$ d based on radio and late-time optical measurements. A fit to the data with a standard jet model in a constant density medium gives reasonable solutions for $\alpha_o \simeq 2.4$.

References. — (1) Costa *et al.* (1997); (2) Reichart (1999); (3) Fruchter *et al.* (2000); (4) Piro *et al.* (1999); (5) Stratta *et al.* (2001); (6) Diercks *et al.* (1998); (7) in 't Zand *et al.* (1998); (8) Reichart *et al.* (1999); (9) Nicastro *et al.* (1999); (10) Halpern *et al.* (1999); (11) Vreeswijk *et al.* (1999); (12) Kulkarni *et al.* (1999); (13) Pian *et al.* (2001); (14) Harrison *et al.* (1999); (15) Sagar *et al.* (2000); (16) Frail *et al.* (2000); (17) Halpern *et al.* (2000); (18) Jensen *et al.* (2001); (19) Berger *et al.* (2001); (20) Price *et al.* (2002); (21) Piro *et al.* (2001); (22) Harrison *et al.* (2001); (23) in 't Zand *et al.* (2001); (24) Galama *et al.* (2003).

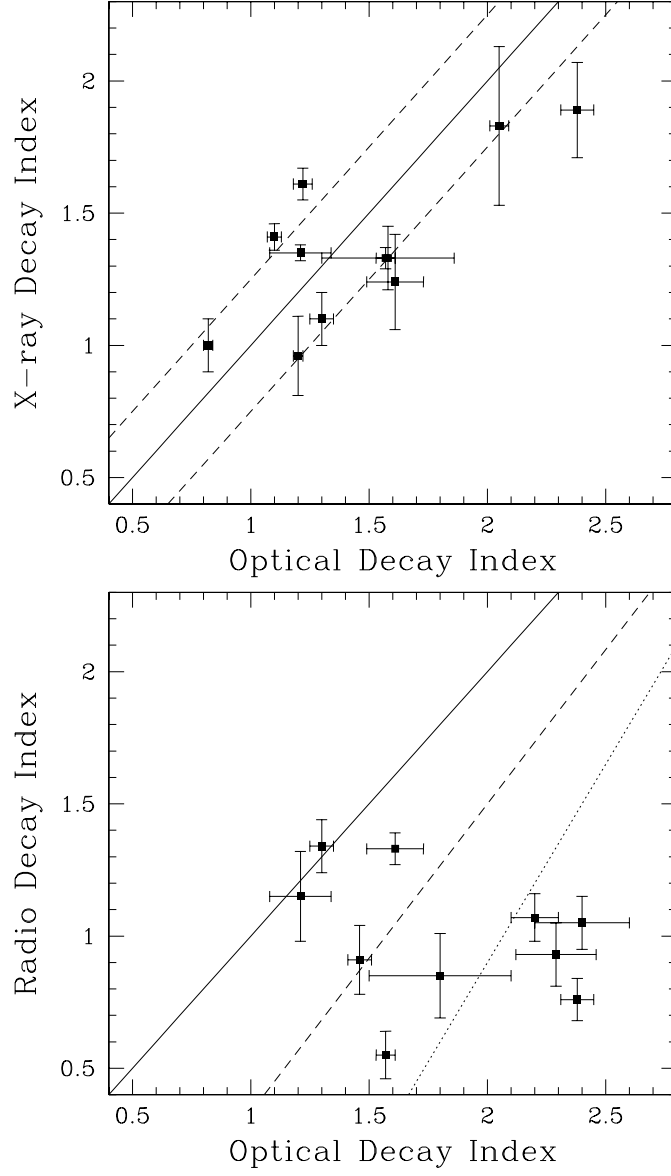


Fig. 1.— The top panel shows the decay indices α defined by $F_\nu \propto t^{-\alpha}$ for a sample of gamma-ray bursts with X-ray and optical afterglows. The solid line corresponds to $\alpha_x = \alpha_o$, while the dashed lines have constant offsets of ± 0.25 . The bottom panel shows decay indices for a sample of bursts with radio and optical afterglows. The solid line is $\alpha_R = \alpha_o$ while the dotted and dashed lines are the expected relation between the relativistic and non-relativistic temporal decay slopes for a jet-like outflow in constant density and wind circumburst media, respectively. In plotting these lines it is assumed that $\alpha_o = -p$ and $\alpha_{NR} = \alpha_R$.

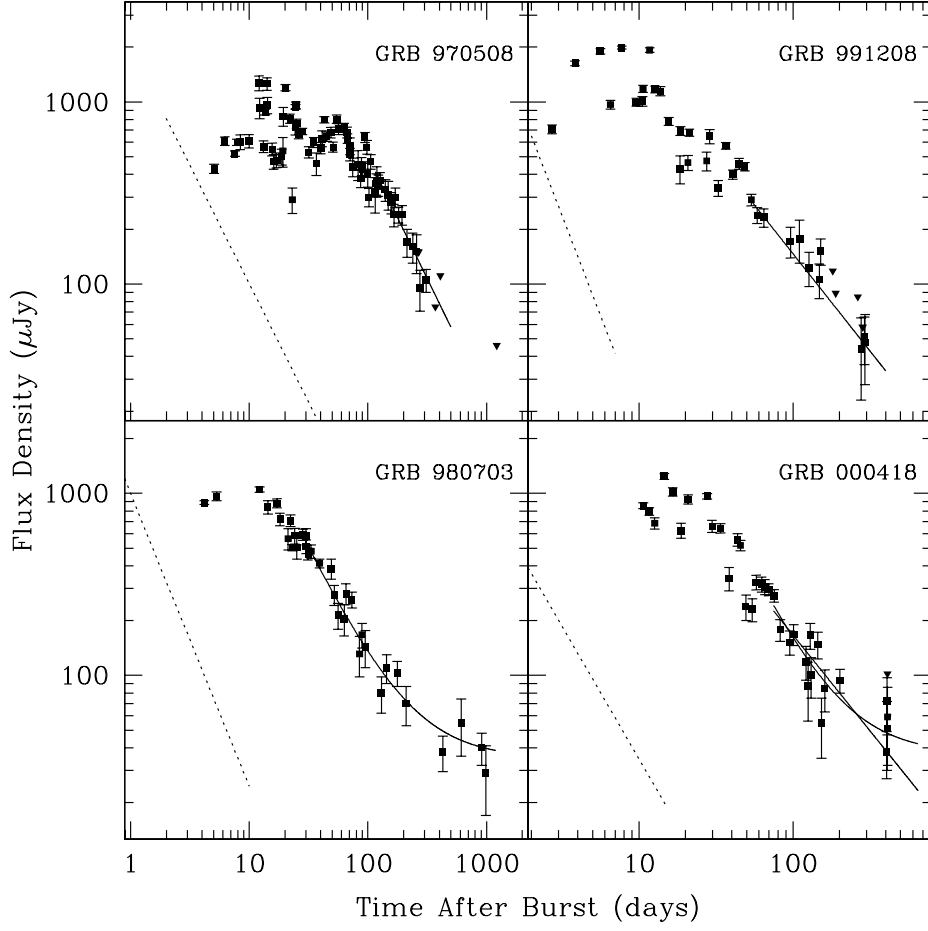


Fig. 2.— Radio light curves of four GRBs at a frequency of 8.46 GHz. A least squares fit was made to the decaying portion of the light curve. The time interval and the slope of each fit is indicated by the solid lines. For GRB 980703 a constant flux density was added to the fit to account for the emission from an underlying host galaxy. For GRB 000418 a pure power-law fit is shown along with a host component included. The slopes of the optical light curves and the time interval over which the fits were made are illustrated schematically with dashed lines.